

# Distinguishing magnetic moment from oscillation solutions of the solar neutrino problem with Borexino

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## Abstract

Assuming that the observed deficit of solar neutrinos is due to the interaction of their transition magnetic moment with the solar magnetic field we derive the predictions for the forthcoming Borexino experiment. Three different model magnetic field profiles which give very good global fits of the currently available solar neutrino data are used. The expected signal at Borexino is significantly lower than those predicted by the LMA, LOW and VO neutrino oscillation solutions of the solar neutrino problem. It is similar to that of the SMA oscillation solution which, however, is strongly disfavoured by the Super-Kamiokande data on day and night spectra and zenith angle distribution of the events. Thus, the neutrino magnetic moment solution of the solar neutrino problem can be unambiguously distinguished from the currently favoured oscillation solutions at Borexino.

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# 1 Introduction

If lepton flavour is not conserved, neutrinos must have flavour-off-diagonal (transition) magnetic moments. Under a transverse magnetic field, such magnetic moments will cause a simultaneous rotation of neutrino spin and flavour, spin-flavour precession [1, 2]. This precession can be resonantly enhanced in matter [3, 4, 5], very much similarly to the resonance amplification of neutrino oscillations, the MSW effect [6].

The resonance spin-flavour precession (RSFP) of solar neutrinos due to the interaction of their transition magnetic moments with the solar magnetic field can account for the observed deficit of solar neutrinos. The conversion mechanism is neutrino energy dependent, which is a necessary feature to fit the data. RSFP requires relatively large values of the neutrino transition magnetic moment,  $\mu_\nu \sim 10^{-11} \mu_B$  for peak values of the solar magnetic field  $B_0 \sim 100$  kG. Although such values of  $\mu_\nu$  are not experimentally excluded, they are hard to achieve in the simplest extensions of the standard electroweak model. Still, the RSFP mechanism yields an excellent fit of all currently available solar neutrino data (see, e.g., [7 – 13] for recent analyses), typically even somewhat better than does the large mixing angle (LMA) oscillation solution, which is the best one among the oscillation solutions. In any case, in pursuit of the solution of the solar neutrino problem it is very important to test all non-standard hypotheses, and neutrino magnetic moment seems to be the most plausible alternative to neutrino oscillations.

Unfortunately, the RSFP solution is difficult to establish experimentally. Except for predicting reduced detection rates of solar neutrinos (which the oscillation solutions also predict), it has mostly negative signatures: No time variations beyond the usual  $1/R^2$  variation due to the eccentricity of the Earth’s orbit (assuming that the strongest component of the solar magnetic field does not vary with time)<sup>1</sup>; no day-night effect; no significant distortions of the solar neutrino spectrum in Super-Kamiokande and SNO experiments. One might therefore think that the RSFP solution of the solar neutrino problem can only be established if all the oscillation solutions are experimentally ruled out. Such a “negative” confirmation would hardly satisfy anyone.

In the present paper we show that in fact this is not the case: the RSFP predictions for the Borexino experiment are very different from those of neutrino oscillations, and different solutions of the solar neutrino problem can therefore be unambiguously distinguished experimentally.

## 2 Predictions for Borexino

The Borexino experiment at Gran Sasso [14], due to start data taking this year, will detect solar neutrinos through the elastic  $\nu e$  scattering. Extremely high radiopurity of the liquid

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<sup>1</sup>There is a caveat here which we shall discuss in Section 3 – this is only true when the solar magnetic field is axially symmetric.

scintillator used and very low background will allow the detection of record low energy recoil electrons. In the electron kinetic energy window  $T_e = 250 - 800$  keV which will be used in the experiment, the major contribution to the signal (78%) is expected from a monochromatic line of  ${}^7\text{Be}$  neutrinos with the energy 863 keV. The next important contributions are from  ${}^{15}\text{O}$ ,  ${}^{13}\text{N}$  and  $pep$  neutrinos (10%, 7.2% and 3.6% respectively), and the predicted detection rate is 55 events/day [14], all according to the BP00 standard solar model [15, 16] and assuming that neutrinos are “standard” (i.e. have no mass, mixing and/or magnetic moment). A lower signal is expected if neutrinos undergo RSFP or oscillations.

We have calculated the expected event rates at Borexino in the case of the RSFP mechanism assuming that neutrinos have Majorana-like transition magnetic moments  $\mu_\nu$  which cause the transitions  $\nu_{eL} \rightarrow \bar{\nu}_{\mu R}$  or  $\nu_{eL} \rightarrow \bar{\nu}_{\tau R}$  in the solar magnetic field. The transition probability depends crucially on the shape and strength of the solar magnetic field which are essentially unknown; one therefore is forced to use various model magnetic field profiles. In our calculations we used three profiles which give very good global fits of the data of the Homestake, Gallex/GNO, SAGE, Super-Kamiokande and SNO solar neutrino experiments [17] (see Table 1 below). The calculation and fitting procedures are described in detail in our previous papers [8], [9] and [13]. Profiles I and II used here are profiles 1 and 6 of ref. [8], whereas profile III of the present paper is profile 4 of ref. [13]. The value of  $\mu_\nu$  was fixed at  $10^{-11}\mu_B$ ; since only the product of the magnetic moment and magnetic field enters in the neutrino evolution equation, our results apply to any other value of  $\mu_\nu$  provided that the magnetic field is rescaled accordingly. We use the “BP00 + new  ${}^8\text{B}$ ” standard solar model, i.e. the solar matter distribution and all the neutrino fluxes except the  ${}^8\text{B}$  one from [15], whereas for the  ${}^8\text{B}$  flux we use the new value [16, 18] which is based on a recent precise measurement of the cross section of the reaction  ${}^7\text{Be}(p, \gamma){}^8\text{B}$  [19]. It is about 17% higher than the previously used value. We have also calculated the Borexino event rates with the “old”  ${}^8\text{B}$  flux and found no significant changes in the results.

Table I: Reduced rates for Gallex/GNO + SAGE, Homestake, Super-Kamiokande and SNO experiments which correspond to the global best fits for the three magnetic field profiles used, along with the corresponding experimental data. The values of  $\chi^2_{min}$  correspond to 39 d.o.f. See the text for more details.

| Profile | $R_{\text{Ga}}$ | $R_{\text{Cl}}$ | $R_{\text{SK}}$ | $R_{\text{SNO}}$ | $\Delta m^2$ (eV <sup>2</sup> ) | $B_0$ (kG) | $\chi^2_{min}$ |
|---------|-----------------|-----------------|-----------------|------------------|---------------------------------|------------|----------------|
| I       | 0.59            | 0.30            | 0.41            | 0.35             | $7.65 \cdot 10^{-9}$            | 45         | 37.8           |
| II      | 0.58            | 0.30            | 0.39            | 0.33             | $1.60 \cdot 10^{-8}$            | 113        | 36.1           |
| III     | 0.58            | 0.30            | 0.40            | 0.33             | $1.48 \cdot 10^{-8}$            | 101        | 35.5           |
| Exp.    | $0.57 \pm .039$ | $0.30 \pm .026$ | $0.39 \pm .014$ | $0.30 \pm .025$  |                                 |            |                |

In Table 1 we give, for the three magnetic field profiles used, the calculated reduced detection rates  $R_i$  (rates assuming RSFP divided by those for “standard” neutrinos) for SAGE+Gallex/GNO (Ga), Homestake (Cl), Super-Kamiokande (SK) and SNO experi-

ments. The indicated rates correspond to the best global fits of the data (all rates plus day and night spectra at Super-Kamiokande). For each profile we show the corresponding best-fit values of  $\Delta m^2$ , peak magnetic field strength parameter  $B_0$ , and  $\chi^2_{min}$  (39 d.o.f.). In the last line we give the experimental detection rates normalized to the “BP00 + new  $^8\text{B}$ ” standard solar model.

As can be seen from the table, all three profiles yield very good global fits of the data. Profile I produces slightly worse a fit than those given by profiles II and III, mainly because it predicts too high a SNO rate. For the “old” values of the  $^8\text{B}$  neutrino flux, the allowed regions of parameters at 95% CL and 99% CL for profiles I and II and for profile III were given in fig. 1 and fig. 2 of ref. [13], respectively. If one uses instead the new  $^8\text{B}$  flux, the allowed regions are slightly shifted (by about 5%) towards higher values of the magnetic field strengths. For illustration, in fig. 1 we show the 95% CL allowed regions for profile III for both old and new  $^8\text{B}$  fluxes.

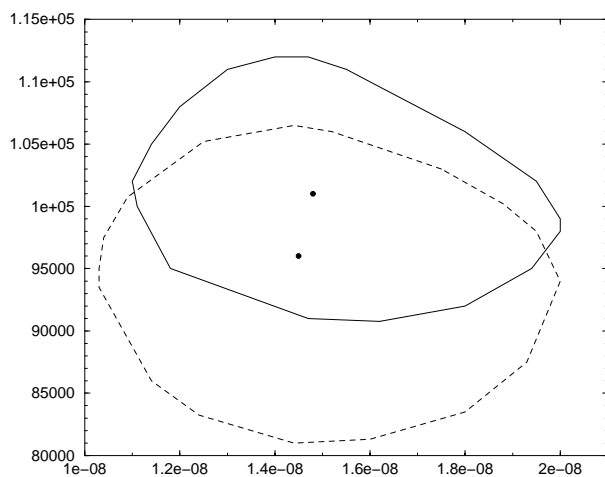


Figure 1: Allowed regions of  $\Delta m^2$  (in  $\text{eV}^2$ ) and  $B_0$  (in G) for profile III at 95% CL. Solid curve – new  $^8\text{B}$  flux, dashed curve – old  $^8\text{B}$  flux. The best fit points are shown by dots.

In Table 2 predictions are given for the reduction factors of the individual contributions of various solar neutrino fluxes to the Borexino event rate (the contributions to the event rate assuming RSFP divided by those for “standard” neutrinos). The results are given, for each of the three magnetic field profiles, for the values of  $\Delta m^2$  and  $B_0$  that produced the best global fits of the currently available data (see Table 1).

Finally, in Table III we present the predicted values of the reduced event rates for Borexino  $R_{\text{Bor}}$ . We give there the values of  $R_{\text{Bor}}$  corresponding to the best-fit values of  $\Delta m^2$  and  $B_0$  as well as the minimum and maximum values of  $R_{\text{Bor}}$  corresponding to the 95% CL and 99% CL allowed ranges of  $\Delta m^2$  and  $B_0$ .

Table II: Reduction factors of the individual contributions of different solar neutrino fluxes to the Borexino event rate. The values of  $\Delta m^2$  and  $B_0$  correspond to the best fits of the present data (see Table 1).

| Profile | $pp$ | $pep$ | ${}^7\text{Be}$ | ${}^{15}\text{O}$ | ${}^{13}\text{N}$ | ${}^8\text{B}$ | $hep$ | total |
|---------|------|-------|-----------------|-------------------|-------------------|----------------|-------|-------|
| I       | 0.71 | 0.18  | 0.29            | 0.26              | 0.32              | 0.44           | 0.47  | 0.28  |
| II      | 0.64 | 0.24  | 0.42            | 0.35              | 0.43              | 0.42           | 0.44  | 0.41  |
| III     | 0.62 | 0.30  | 0.35            | 0.35              | 0.39              | 0.44           | 0.46  | 0.35  |

Table III: Predicted reduced event rates for Borexino  $R_{\text{Bor}}$ .

| Profile | b.f. | min (95% CL) | max (95% CL) | min (99% CL) | max (99% CL) |
|---------|------|--------------|--------------|--------------|--------------|
| I       | 0.28 | 0.21         | 0.50         | 0.21         | 0.57         |
| II      | 0.41 | 0.29         | 0.57         | 0.28         | 0.62         |
| III     | 0.35 | 0.31         | 0.52         | 0.30         | 0.57         |

### 3 Discussion

The main goal of this work was to investigate whether RSFP can be distinguished from the oscillation solutions of the solar neutrino problem at Borexino. There are four main types of oscillation solutions of the solar neutrino problem, depending on the allowed values of the leptonic mixing angle  $\theta$  and neutrino mass squared difference  $\Delta m^2$ : Large mixing angle (LMA), small mixing angle (SMA) and low- $\Delta m^2$  (LOW) MSW solutions, and also vacuum oscillation (VO) solution (for recent discussions see, e.g., [20, 21, 18, 22, 23, 12]). The LMA, LOW and VO solutions all predict the average suppression of the event rate at Borexino by 35 – 40%, whereas in the case of the SMA solution a suppression by about a factor of five is expected.

The main feature of the RSFP mechanism which can be exploited in order to distinguish it experimentally from neutrino oscillations is the peculiar shape of the energy dependence of the survival probability of solar neutrinos: At high energies it resembles the  $\nu_e$  survival probability of the LMA oscillation solution, whereas at low energies it is similar to that of the SMA solution. A mismatch in the results of the experiments sensitive to the high-energy and low-energy parts of the solar neutrino spectrum would therefore be an indication for RSFP.

As can be seen from Table III, the RSFP mechanism predicts the suppression of the event rate at Borexino by about a factor of three. The maximum allowed at 99% CL reduced rate is 0.62; this only marginally overlaps with the minimum allowed at  $3\sigma$  reduced rate in the case of the LMA solution (0.58, see Table 7 of ref. [18]). Thus, the predictions of the RSFP and LMA solutions are more than  $5\sigma$  away from each other and the probability of mistaking one for another is very low.

The minimum allowed at  $3\sigma$  values of the reduced rate at Borexino in the case of LOW and VO solutions, 0.54 and 0.53 respectively [18], are slightly lower than that for the LMA solution, so that there is a larger overlap with the 99% CL prediction of the RSFP. However, in these cases, too, one can easily discriminate between RSFP and the oscillation solutions. Indeed, in the case of the LOW solution one expects a sizeable (up to 40%) day-night event rate difference at Borexino, while VO should lead to large seasonal variations beyond the usual  $1/R^2$  dependence. No such effects are predicted by RSFP.

Our predictions for the reduced event rate at Borexino in the case of RSFP are slightly higher than those of the SMA oscillation solution, although there is a significant overlap between the predicted rates in these two cases. It should be noted, however, that the SMA solution is strongly disfavoured by the data on day and night spectra and zenith angle distributions of recoil electrons at Super-Kamiokande [24]. We therefore conclude that Borexino will allow a clear discrimination between RSFP and currently favoured oscillation solutions of the solar neutrino problem. It should be noted that new dedicated low-energy solar neutrino experiments, which are widely discussed now [25], should have a similar or even stronger discriminative power <sup>2</sup>.

The RSFP mechanism may also lead to some specific effects, absent in the case of neutrino oscillation solutions. If the solar magnetic field is not axially symmetric, the rotation of the Sun can lead to a time variation of the signal with the period equal to the solar rotation period (about 28 Earth's days). Another possible signature of RSFP is an observable flux of  $\bar{\nu}_e$  from the Sun if neutrinos, in addition to transition magnetic moments, have a sizeable flavour mixing ( $\theta \gtrsim 0.1$ ) [26]. The flux of solar  $\bar{\nu}_e$ 's at the level of 1% of the  $\nu_e$  flux can, in principle, be detected at Borexino and SNO. However, these signatures depend on additional assumptions about  $\theta$  and the structure of the solar magnetic field, whereas our predictions for the Borexino detection rate are essentially model independent. The only possible model dependence is contained in the choice of the solar magnetic field profile, and this freedom is severely constrained by the requirement of fitting the available solar neutrino data. As a result, the predictions for the Borexino event rate, though somewhat different for different profiles (see Table III), all fall below those for the LMA, LOW and VO solutions.

In conclusion, we have shown that the Borexino experiment will be able to unambiguously distinguish RSFP from the currently favoured oscillation solutions of the solar neutrino problem.

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